

# **Experimental and Numerical Investigation of Reduced Gravity Fluid Slosh Dynamics for the Characterization of Cryogenic Launch and Space Vehicle Propellants**

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## **ABSTRACT**

As space programs increasingly investigate various options for long duration space missions the accurate prediction of propellant behavior over long periods of time in micro-gravity environment has become increasingly imperative. This has driven the development of a detailed, physics-based understanding of slosh behavior of cryogenic propellants over a range of conditions and environments that are relevant for rocket and space storage applications. Recent advancements in computational fluid dynamics (CFD) models and hardware capabilities have enabled the modeling of complex fluid behavior in micro-gravity environment. Historically, launch vehicles with moderate duration upper stage coast periods have contained very limited instrumentation to quantify propellant stratification and boil-off in these environments, thus the ability to benchmark these complex computational models is of great consequence. To benchmark enhanced CFD models, recent work focuses on establishing an extensive experimental database of liquid slosh under a wide range of relevant conditions. In addition, a mass gauging system specifically designed to provide high fidelity measurements for both liquid stratification and liquid/ullage position in a micro-gravity environment has been developed. This publication will summarize the various experimental programs established to produce this comprehensive database and unique flight measurement techniques.

**KEYWORDS:** Liquid slosh, micro-gravity, mass gauging, cryogenics, launch vehicle

## INTRODUCTION

Upper-stages of rockets may undergo maneuvers, which may lead to sloshing of the liquid propellants and may adversely affect vehicle performance. For example, liquid motion may generate reaction forces that alter the motion of the vehicle from its intended trajectory or cold cryogenic propellants may splash on warm tank surfaces leading to changes in the thermodynamic state of the propellant. An additional consideration in launch vehicle design is the potential overlap of slosh resonant frequencies with the trajectory control system and structural dynamics frequencies. Each of these potentially detrimental situations underscores the need for experimentally benchmarked CFD model, which would be crucial to plan future space missions.

## EXPERIMENTAL SLOSH CHARACTERIZATION AND NUMERICAL METHODS

Experimental data that allows full characterization of a slosh event is achieved via synchronous capture by an array of cameras, accelerometers, and gyroscopic sensors. The time history of the tank relative to an inertial frame is sufficient to characterize a slosh event, provided that the initial liquid distribution is known [1,2]. This approach is based on the simultaneous measurement of the acceleration of the tank, the angular velocity, and the three components of the heading vector. In this paper, two categories define any given liquid slosh motion over a range of environments:

1. Forced motion of a rigid container: This category is applicable when fluid forces pushing back on the tank walls do not affect the prescribed motion of the tank. The motion of the tank is independent of the sloshing forces acting on the container.
2. Coupled motion of the tank and the sloshing liquid: If the container's motion is not constrained, the sloshing liquid generates forces that push back on the container and may alter its trajectory. This is especially important in suborbital applications such as upper-stage launch vehicles.

FIGURE 1 illustrates the differences in these two categories by comparing the motion between a hollow cylinder with a solid bottom and an identical cylinder partially filled with liquid, when subject to the same multi-axis initial acceleration conditions, followed by multi-axis free motion. The center of mass of the bottom cylinder varies with time because of the redistribution of the liquid due to the influence of inertial slosh forces on the walls of the tank.

A numerical simulation technique for category 1 experimental approach would only require a fluid dynamics solver; however, the category 2 experimental approach would require coupling a fluid dynamics solver and a rigid body dynamics solver [1,2]. Coupled numerical simulation would require, for a single iteration, the tank's motion to

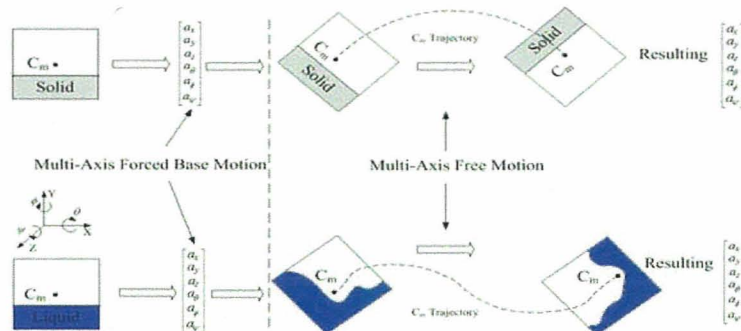


FIGURE 1. Influence of solid force and liquid slosh force to a prescribed tank motion



be solved in the rigid body dynamics solver and the solution to be transferred to the fluid dynamics solver. The liquid behavior is then calculated using the dynamic tank wall boundaries and the resulted liquid forces acting on the tank walls would transfer back to the rigid body dynamics solver for the next iteration. The rigid body dynamics solver assumes that any motion of a rigid body can be split into translational and rotational motions. Appropriate grid resolution is critical to achieving good results using any CFD method. In particular, the mesh near the tank walls must be sufficiently refined to capture capillary action and wall wetting.

## EXPERIMENTAL AND COMPUTATIONAL RESULTS

This section presents examples from successful experiments performed over varied conditions, which offer diverse sloshing events. The different variety of sloshing events due to different conditions challenges the CFD tool with a unique opportunity to validate each set of sloshing events. This paper details three major experiments from three different categories: 1. Ground- based experiments, 2. Simulated micro-gravity experiments and 3. Long duration micro-gravity experiments. Liquid sloshing events due to each experiment are recorded and compared to CFD model predictions.

### Ground- Based Experiments

Ground-based experiments are a useful first step to test the accuracy of CFD models as well as the robustness of the instrumentation and data acquisition of the experiment. A forced motion table developed by Florida Institute of Tehcnology was utilized to perform a series of experiments in both category 1 and category 2. FIGURE 2 and FIGURE 3 shows the overview of the capabilities of the slosh platform. The container geometry is a cylinder with flat end caps and has the option of including an anti-slosh baffle; the tank sits on a single-axis computer-controlled platform. The platform is currently capable of two-degree of freedom (2DOF), one being linear translation in x-axis (FIGURE 2) and other being free rotation in y-axis (FIGURE 3). Data acquisition plays a pivotal role in slosh experimentation because the assumptions that form the input for CFD are from the experimental results. The acceleration experienced by the tank and captured by the tri-axial accelerometer provide the data from accelerometers that form the input conditions for the CFD model. The other important aspect of this work is image-capturing technique, which plays an important part in comparing results between experiment and CFD. The whole process of initializing the experiment, data acquisition and synchronized image capturing,

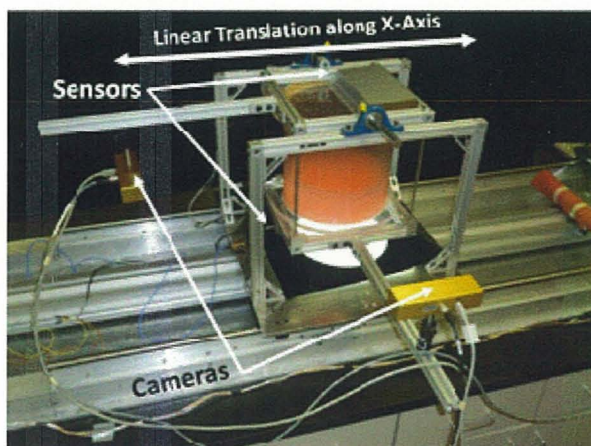


FIGURE 2. Forced linear translation (constrained)

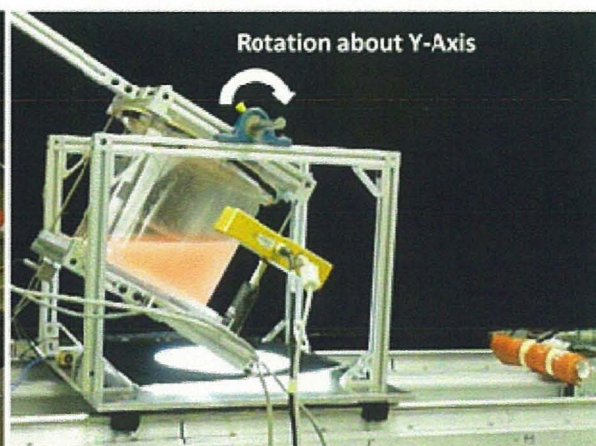
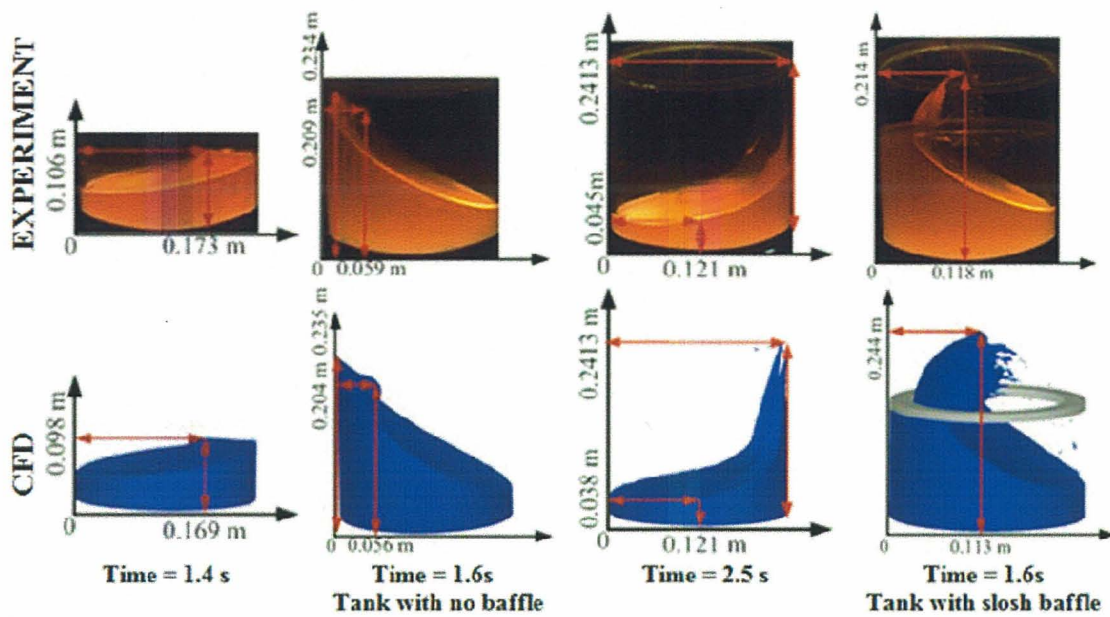


FIGURE 3. Free rotation at y-axis (unconstrained)

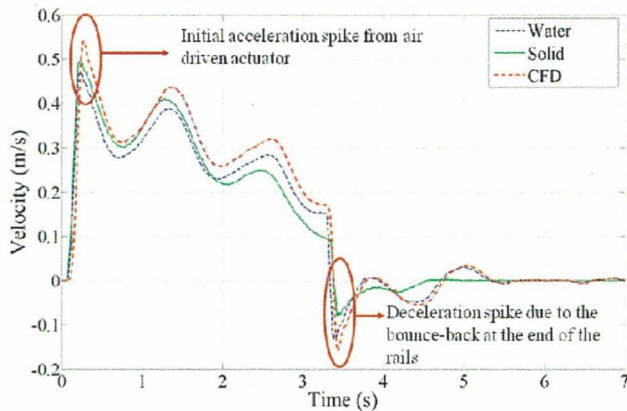


**FIGURE 4.** Example of experiment (top row) and CFD results (bottom row) for a forced linear motion

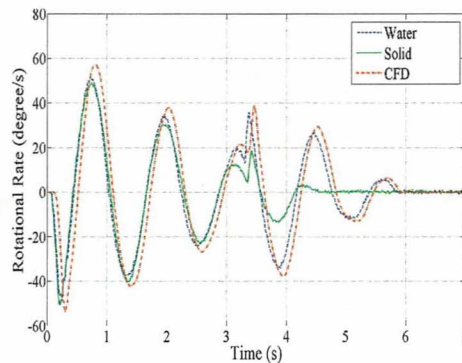
controlled via LabView and the data gathered is post processed in MATLAB.

FIGURE 4 shows a comparison of the forced motion category 1 approach with the series of pictures on the top row being experimental results and bottom row being CFD results. The time stamp for each snap shot for experimental and CFD is given below the pictures. The last column in FIGURE 4 is an example of tank with slosh baffle. This series of pictures are demonstration of the CFD tool to predict accurately the liquid-gas interface during a chaotic motion of tank. Comparing results for peak amplitude, interface height between experiment and CFD results show that the level of agreement is better than 5%.

To capture the coupling effects of liquid slosh forces on the motion of a container, the category 2 type experiment approach was undertaken. In this experiment, neither the container rotation nor the base translation is constrained after an initial external impulse is applied. A compressed air powered piston creates an adjustable, and repeatable initial input acceleration to the base of the platform. The test setup included two tri-axial accelerometers, one gyroscopic angular velocity sensor attached to the pivot shaft, and an incremental encoder. Experiments performed utilized a liquid (water) and a solid block,



**FIGURE 5.** Velocity profile comparison



**FIGURE 6.** Rotation rate comparison



which was then replicated using the CFD tool. The solid block was preferred in simulation because of its predictive and simplified inertial motion it would impart to the tank. The results for the liquid tests, solid block tests and the corresponding liquid CFD simulations were benchmarked using the linear velocity plot (FIGURE 5) and the rotation rate plot (FIGURE 6) from the gyroscopic sensor data. The velocity plot of the water test deviated a maximum of 43.04% compared to the solid test at 0.002 m<sup>3</sup> fill level, and the deviation reduced to a maximum 28.95% at the 0.004 m<sup>3</sup> fill level. Observation of rotation rate comparison shows a similar trend, with the same initial acceleration, the system gained less momentum at low fill level. The less momentum gained by the entire system, the more the liquid motion affected system's motion due to the liquid to solid mass ratios, as seen on the previous tests group. A general good agreement between water tests and CFD simulations was found: the average difference in results (CFD compared to measured data) varied from 8.74% to 10.53%.

## Simulated Micro-gravity Experiments

NASA's micro-gravity aircraft, operated by the Johnson Space Center, creates approximately 10-30 second intervals of micro-gravity in a coordinate system attached to the plane by flying in parabolic flight trajectory [3,4]. As in ground-based testing, the slosh event is due to rigid body motion of the tank relative to an inertial frame. The exception is that the flight path causes fluid slosh, within an aircraft-induced micro-gravity environment. This is a typical category 1 experiment approach, where the fluid sloshing inside does not affect the rigid tank motion. The 6-DOF acceleration of the tank can be input to the Dynamic mesh model (DMM) tool, and the numerical results compared to the acquired images frame-by-frame. The aircraft's accelerometer data from a typical flight maneuver shown in FIGURE 7, illustrates the three phases of a typical reduced gravity parabolic maneuver; in these experiments, micro-gravity fluctuates within  $\pm 0.05$  g. FIGURE 8 shows water sloshing inside of a tank at 11 seconds during the typical dive of the flight, which create a sudden loss of gravity (free fall). During the aircraft's climb, the liquid motion established by inertial forces inherent to the flight maneuver dominates capillary forces. The aircraft's climb creates a slosh wave that is dependent on the pilot's control of maneuver entry and nose-over. Small yaw and roll perturbations cause differences in acceleration among successive data sets. The 1.8 g climb settles the liquid at the bottom of the tank prior to the slosh wave generated by the aircraft's pitch deceleration.. In this case, purely capillary forces dominate [5, 6].

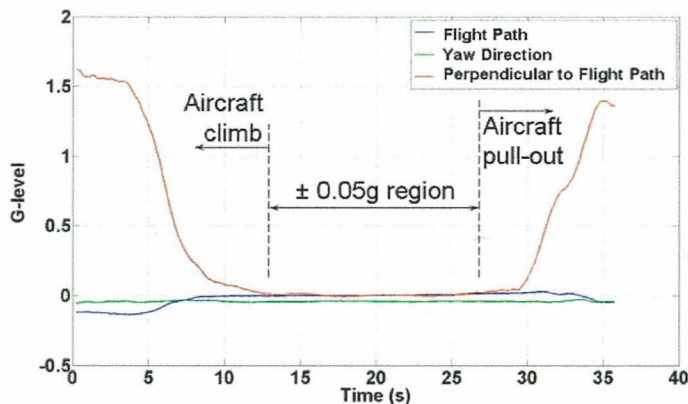


FIGURE 7. Acceleration profile of aircraft

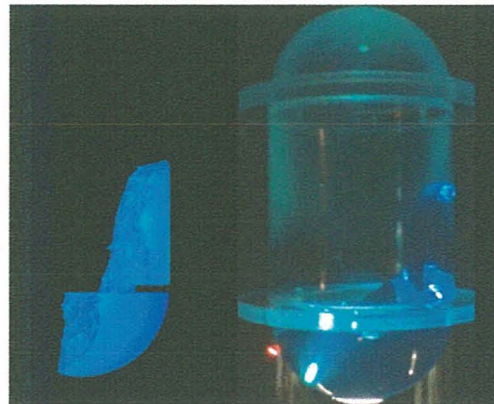


FIGURE 8. CFD (left) vs. exp (right)

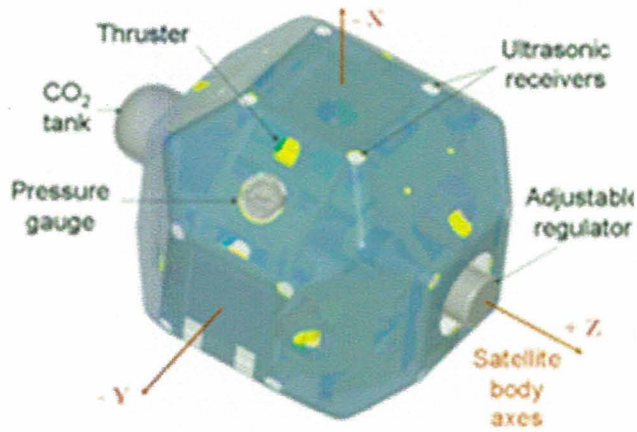


FIGURE 9. MIT SPHERES

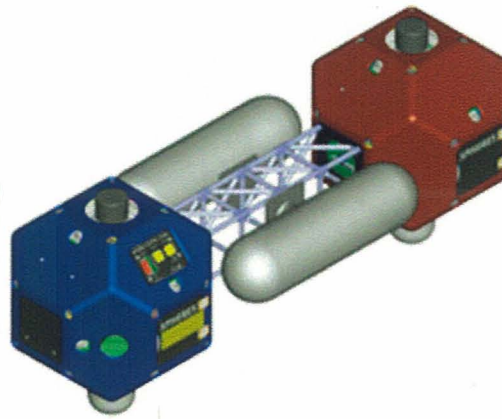


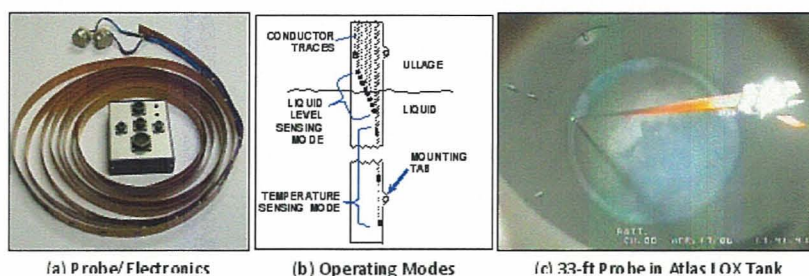
FIGURE 10. Future twin SPHERES concept

## Long Duration Micro-gravity Experiments

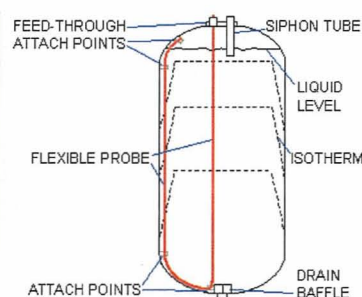
Simulated micro-gravity has shortcomings, one being it is a category 1 experimentation approach and the other being a shorter time interval of simulated micro-gravity. These shortcomings are not relevant if the experiments performed would be in an actual micro-gravity environment. Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) an experimental platform developed initially at Massachusetts Institute of Technology (MIT), consists of small free-flying satellites, each with CO<sub>2</sub> cold gas thrusters and a thruster fuel tank. FIGURE 9 shows the schematic of experimental platform, which is highly beneficial due to its small size and the location of the experiment, the International Space Station (ISS). An example test would be a partially filled SPHERES's thruster tank fired for a short duration from a specific face with the tank, settling after mitigation of sloshing events inside. The duration of experiment is not critical, but the magnitude and duration of single or multiple thrust events must be controlled so as not to collide with space station walls. Information and data provided by SPHERES program, as the tank and satellite responded to the thrust event, was crucial in understanding fluid behavior in micro-gravity environment, and validation with CFD reinforced the reliability of CFD models to quantify accurately the sloshing events.

The success of SPHERES project dictated the need to push the envelope of complexity involved in modeling slosh in micro-gravity. It was desired to determine if the CFD model could accurately predict a combined twin tank with different fluid or fill levels undergoing different slosh modes due to the motion of launch or spacecraft vehicles. It became important to establish scenarios common with docking procedures for launch vehicles, fuel depots in space, and satellites; hence, a concept has been created based on the initial SPHERES project, utilizing two SPHERES and two liquid propellant tanks representing a launch or space vehicle. The 6DOF motion would be created via an array of cold-flow CO<sub>2</sub> thrusters supplied from the built-in liquid CO<sub>2</sub> tank. The DMM model would predict the effect of the liquid CO<sub>2</sub> slosh within the simulated tanks based on the 6-DOF trajectory of the SPHERES satellite. This would be accomplished by applying a prescribed thruster impulse to the two satellites, one with a full CO<sub>2</sub> tank and a second one with a near-empty CO<sub>2</sub> tank. In both cases, the resulting 6DOF motion would be captured, the differences being attributable to the different CO<sub>2</sub> slosh motion inside of the tank. The 6DOF force and torque thrust vectors would form inputs to the DMM simulation, and the slosh responses and predictions would then be compared to the recorded trajectories.

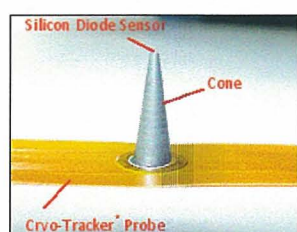




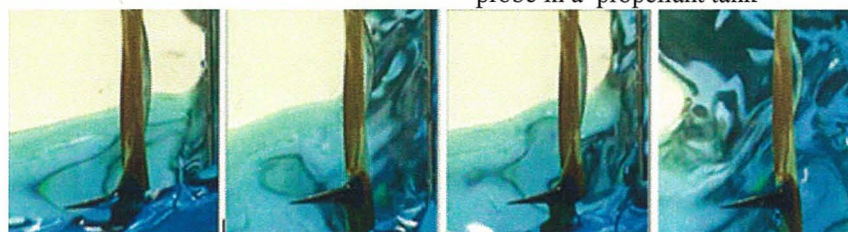
**FIGURE 11. Cryo-Tracker® Mass Gauging System**



**FIGURE 12. Cryo-Tracker® probe in a propellant tank**



**FIGURE 13. Probe Mounted Sensor**



**FIGURE 14. In Flight Reduced Gravity Sensor – Parabola 16**

## MASS GAUGING SYSTEMS FOR HIGH FIDELITY CHARACTERIZATION OF FLUID POSITION

Real-time monitoring of cryogenic propellants in long term space vehicles, in addition to CFD predictions is critical for assuring mission success and assessing the states of the propellants and propellant management systems. A high fidelity mass gauging system designed to operate in micro-gravity has been developed to provide such data. The Reduced Gravity Cryo-Tracker® (RGCT) Mass Gauging System (MGS)[7] is an expansion of the Cryo-Tracker® MGS (FIGURE 11 and FIGURE 12) designed to provide both high fidelity liquid level and temperature measurements with a mechanical flexibility that allows the probe to conform to any tank geometry, for tank fill, boil-off control, and drain events. The automated sensing system has been tested in a simulated launch vehicle tank in LN<sub>2</sub> at the Kennedy Space Center Cryogenics Test Laboratory[9], in LOX in the Lockheed Martin Atlas test tank in Denver, CO. (FIGURE 11) [10] and in LH<sub>2</sub> [11]. The system was proven to withstand rapid fill and drain conditions simulating engine burn and shut down while delivering highly accurate mass gauging data. The geometric cone sensor design of the RGCT (FIGURE 13), based on the work of Berns *et al.* [7], and enhanced specifically for the applications of cryogenic propellant tanks in long term micro-gravity environments, has been extensively tested through the use of the the NASA micro-gravity research aircraft. Test visualizations demonstrate the ability of the sensor and probe system to detect the presence of liquid or vapor states with a high level of accuracy (FIGURE 14) during micro-gravity induced capillary action. Flight sensor data demonstrates the system's ability to correctly detect liquid or vapor states reliably and with a high level of accuracy. The RGCT has since been advanced to a flight design with avionics and mass gauging probes intended for cryogenic fluid management demonstrations utilizing secondary payloads on space launch vehicles. .

## CONCLUSIONS AND FUTURE WORK

Recent advances in CFD capabilities have enabled the modeling of liquid rocket propellant behavior in the micro-gravity environment of space. This paper presented a wide range of experiments performed and validated in different conditions and environments. An



experimental framework for characterization of slosh events makes use of a frame-by-frame image of the sloshing liquid surface synchronized to the corresponding 6DOF acceleration time history of the tank. The measured acceleration history used as the input into CFD codes and the results compared with data images acquired from the experiment. Modern CFD tools, such as the DMM are capable of replicating slosh events over a wide range of conditions. Validation for the tool in works against complex situations, which include liquid slosh force feedback on the container and thermal effects, such as stratification and boil-off.

A mass gauging system designed to provide high fidelity measurements for both liquid stratification and liquid/ullage position in a micro-gravity environment has been developed to provide additional experimental data to benchmark CFD codes.

Future work slosh dynamics research will include a ground-based testing of cryogenic nitrogen to capture boil-off effects. Additional SPHERES experiments performed using combinations of multiple larger propellant tanks to test more aggressive slosh scenarios for extended durations. Flight-testing of the mass gauging system is planned on a new upper-stage vehicle experiment called the **CRYogenic Orbital TEstbed** (CRYOTE).

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Zhou, R., Vergalla, M., Gutierrez, H., and Kirk, D., Experimental and Numerical Investigation of Liquid Slosh Behavior Using Ground-based Platforms, AIAA Journal of Spacecraft and Rockets, October 2011.
2. Vergalla, M., Zhou R., Gutierrez, H., and Kirk, D., "Experimental and Numerical Framework for Characterization of Slosh Dynamics," International Review of Aerospace Engineering, ISSN 1973-7459, Vol. 2, N. 1, February 2009.
3. Zappa, B. et. al., On the Number and Placement of accelerometers for Angular Velocity and Acceleration Determination, Transactions of the ASME, Vol. 123 (2001).
4. Del Rosso, D., Experiment Design Requirements and Guidelines, AOD 338997 RevC, NASA 932 C-9B. Lyndon Johnson Space Center Houston, Texas. Nov. 2007.
5. Michaelis, Mark and Michael, Dreyer E., Test-case number 31: Reorientation of a Free Liquid Interface in a Partly Filled Right Circular Cylinder upon Gravity Step Reduction (PE)., 28359 Bremen, Germany : ZARM, University of Bremen, 2003.
6. Mourik, S. van, Veldman, A.E.P. and Dreyer, M.E. Simulation of Capillary Flow with a Dynamic Contact Angle, Bremen, Germany : Z-Tec Publishing, Bremen Microgravity sci. technol. XVII-3, 2005.
7. Habermus, Mark S.; Lawless, Branden J.; Ickes, Jacob C.; Walls, Laurie K.; "Reduced Gravity Cryo-Tracker® System," 47th AIAA Aerospace Sciences Meeting, Orlando, FL, AIAA Paper 2009-1599, January 2009.
8. Berns, James A., Yeh, Frederick C., and Nussle, Ralph C., "Photographic Investigation of Liquid Behavior on Temperature and Liquid-Vapor Sensors used in Low-Gravity Environment," NASA TM X-1438, 1967.
9. Scheib, Daniel J., Habermus, Mark S., and Yeckley, Alexander J., "Cryo-Tracker® Mass Gauging System Testing in a Launch Vehicle Simulation," Vol. 51 by the American Institute of Physics, presented at Cryogenic Engineering Conference, Keystone, CO, August 2005.
10. Schieb, Daniel J., Habermus, Mark S., and Yeckley, Alexander J., "Cryo-Tracker® Mass Gauging System Testing in a Large-Scale Expendable Launch Vehicle LOX Tank Simulator," 2006 SPIE Defense and Security Symposium, Orlando, FL, April 2006.
11. Habermus, Mark S. and Bryant, C.B., "Liquid Hydrogen Testing of an Ultra-Light Flexible Temperature and Liquid Level Sensing Probe," Proceedings of 48th International Instrumentation Symposium, San Diego, CA, 2002.





# Experimental and Numerical Investigation of Reduced Gravity Fluid Slosh Dynamics for the Characterization of Cryogenic Launch and Space Vehicle Propellants

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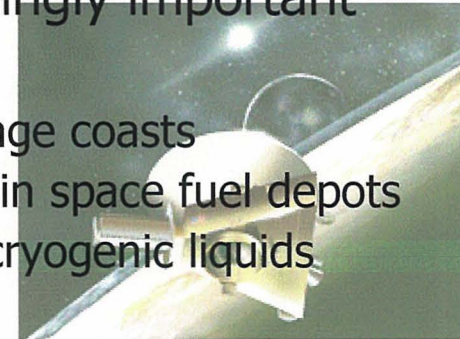


# Introduction



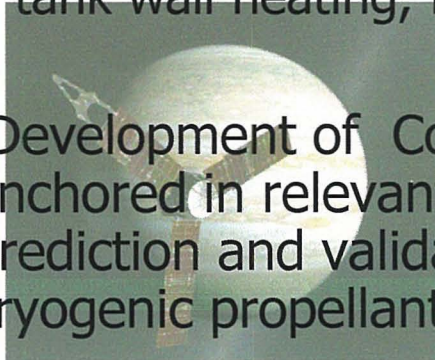
– The investigation of slosh dynamics in cryogenic propellant tanks of launch and space vehicles has become increasingly important

- Planetary launches often require extended upper stage coasts
- Proposed long duration space missions may involve in space fuel depots
- Planetary spacecraft and landers frequently utilize cryogenic liquids



– Stringent mass requirements drive precision control and management of propellant reserves

- In space vehicle maneuvers drive slosh events that can cause severe tank wall heating, liquid boil-off and asymmetric mass flow



– Development of Computational Fluid Dynamic (CFD) models anchored in relevant experimental data has become imperative for prediction and validation of complex space induced environments for cryogenic propellants

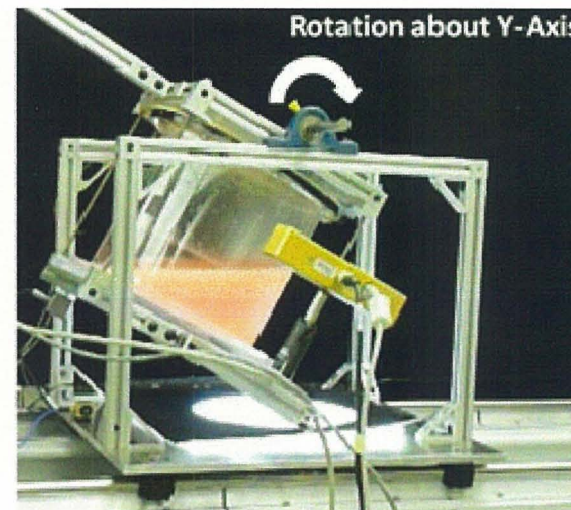
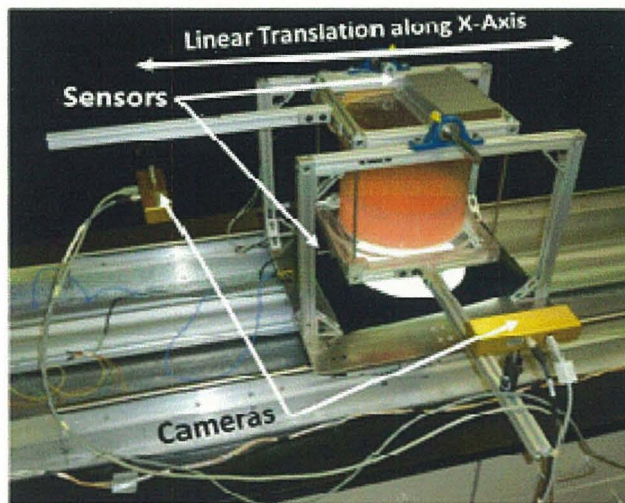




# Experimental Characterization



- NASA/Florida Institute of Technology collaboration
  - Ground based platforms designed to validate CFD models and replicate micro-gravity environments and events



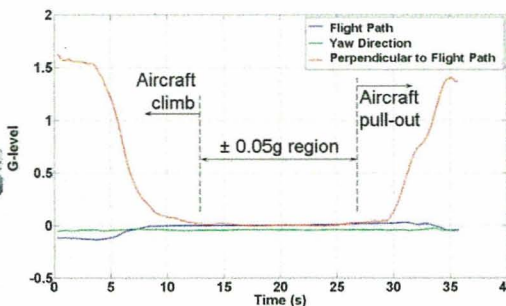
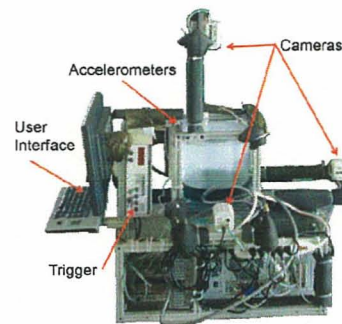
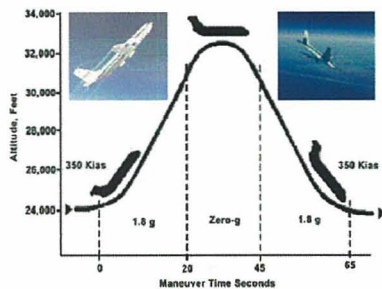
- Capable of forced motion linear translation and free rotation
- Data acquisition includes stereo cameras, accelerometers and gyroscopic sensors
- Provides input for CFD models and liquid responses



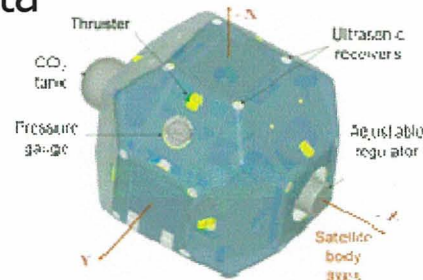
# Experimental Characterization



- Micro-gravity investigations also include flights on NASA's Reduced Gravity Aircraft (RGA) and International Space Station (ISS) experiments
  - Limitations of RGA include initial settling of liquid due to high-G climb and  $\sim 20$  seconds of micro-gravity



- Massachusetts Institute of Technology developed Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) utilized to collect longer term data



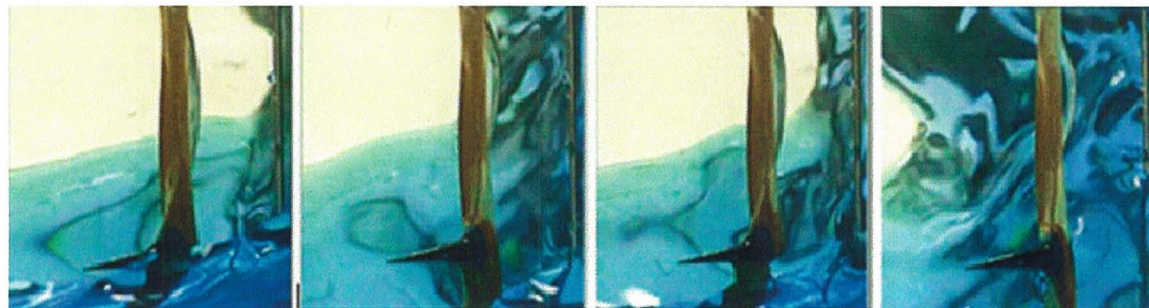
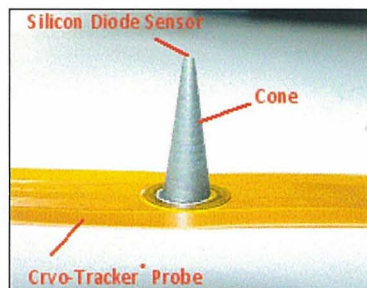
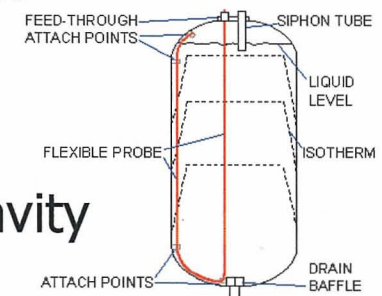




# Reduced Gravity Mass Gauging System



- Development of a Reduced Gravity Cryo-Tracker (RGCT) addresses the necessity of high fidelity continuous in-flight measurement and propellant management control
  - Collaboration between NASA and Sierra Lobo, Inc.
  - Utilizes patented Cryo-Tracker mass gauging probe
  - Sensors designed to account for effects of micro-gravity environment
  - Flight tested on RGA with accurate and repeatable results
  - Probe design and avionics advanced for use on a space-based Cryogenics Fluids Management Testbed

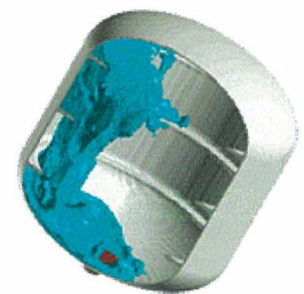
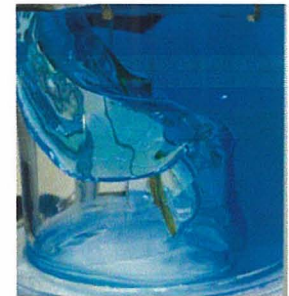
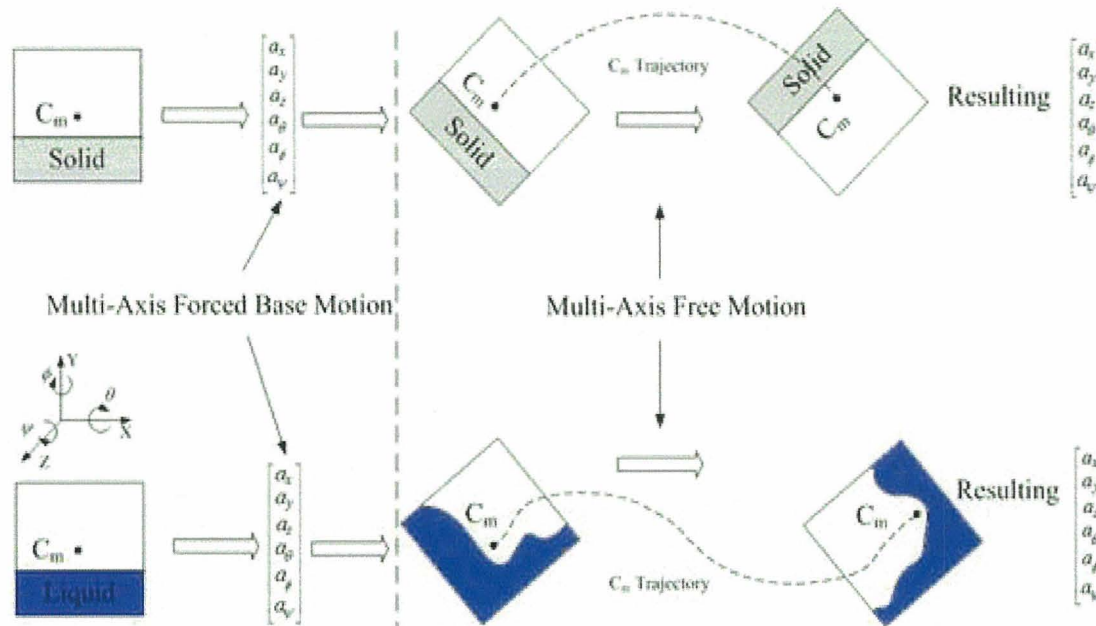
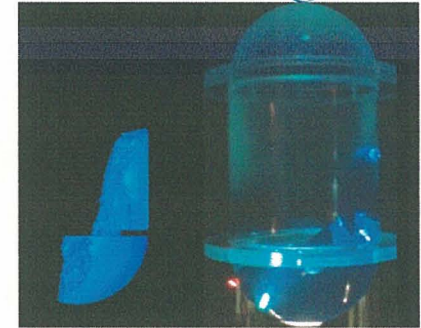




# Computational Representations



- Two methods of numerical simulation
  - Forced motion of a rigid container
  - Fluid forces on tank wall do not affect prescribed tank motion
  - Coupled motion of tank and sloshing liquid
  - Reactive liquid forces on tank alter trajectory





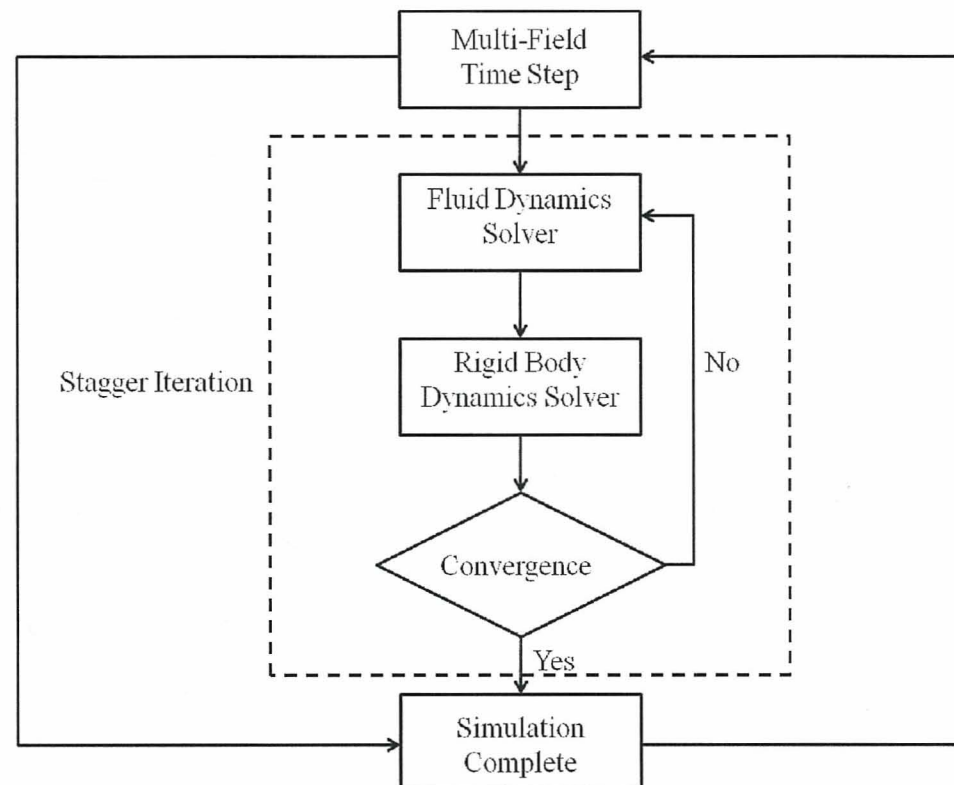


# Numerical Simulation



## – Coupled fluid and rigid body dynamics solver

- At each iteration tank motion in rigid body dynamics solver
- Solution then transferred to fluid dynamics solver
- Liquid behavior calculated using dynamic tank wall boundaries
- Resulting forces transferred back to rigid body dynamics solver

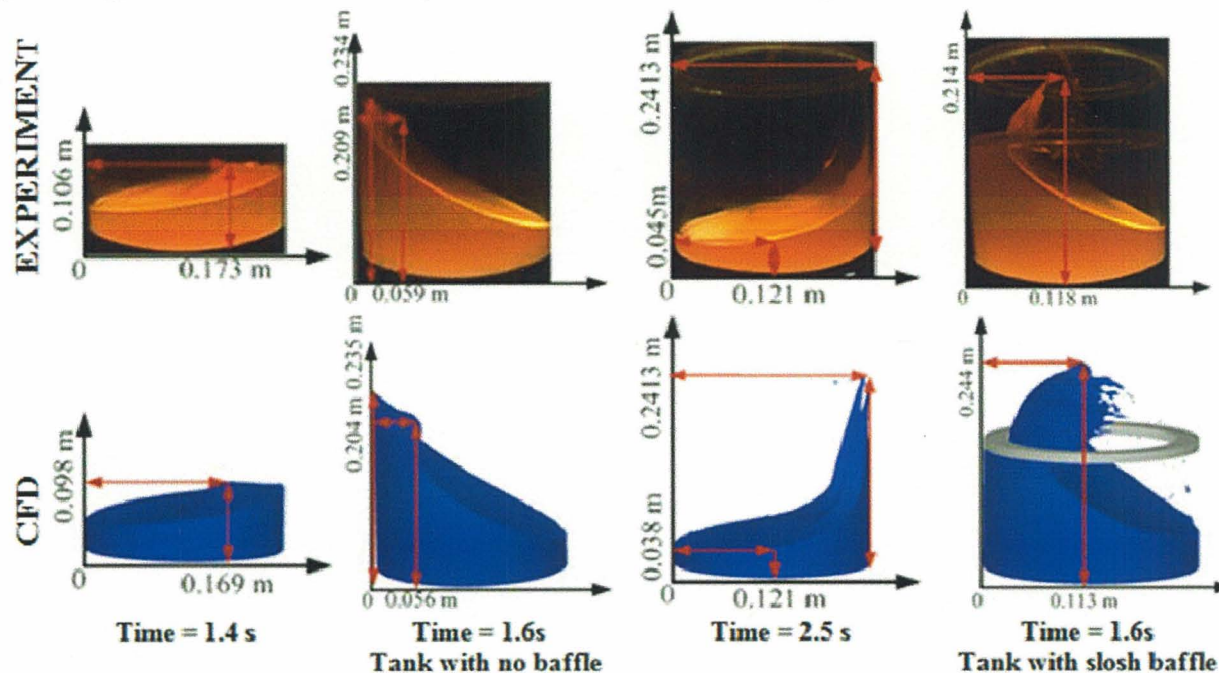




## Comparison of Results



- Comparison of CFD and experimental results for a forced linear motion
  - Liquid gas interface predictions during chaotic tank motions



- Peak amplitude and interface heights demonstrate good agreement

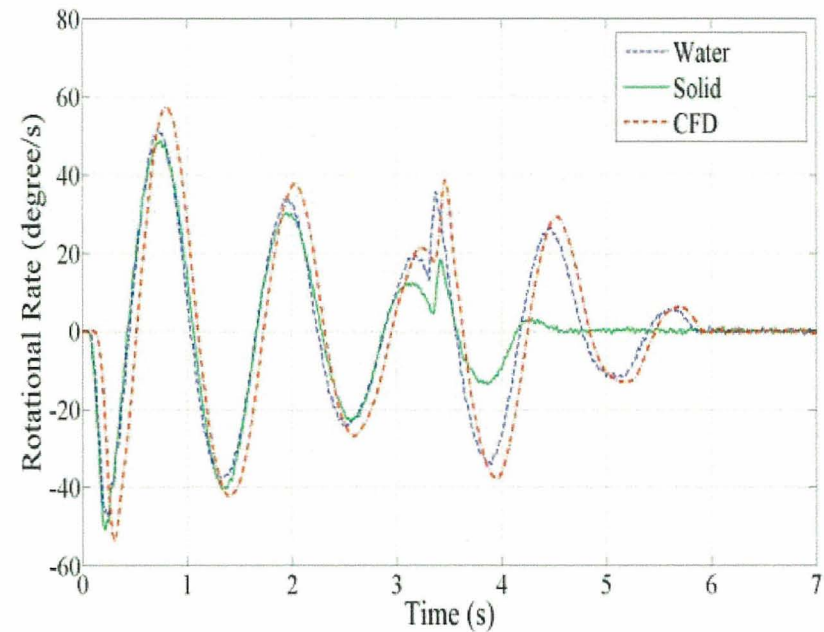
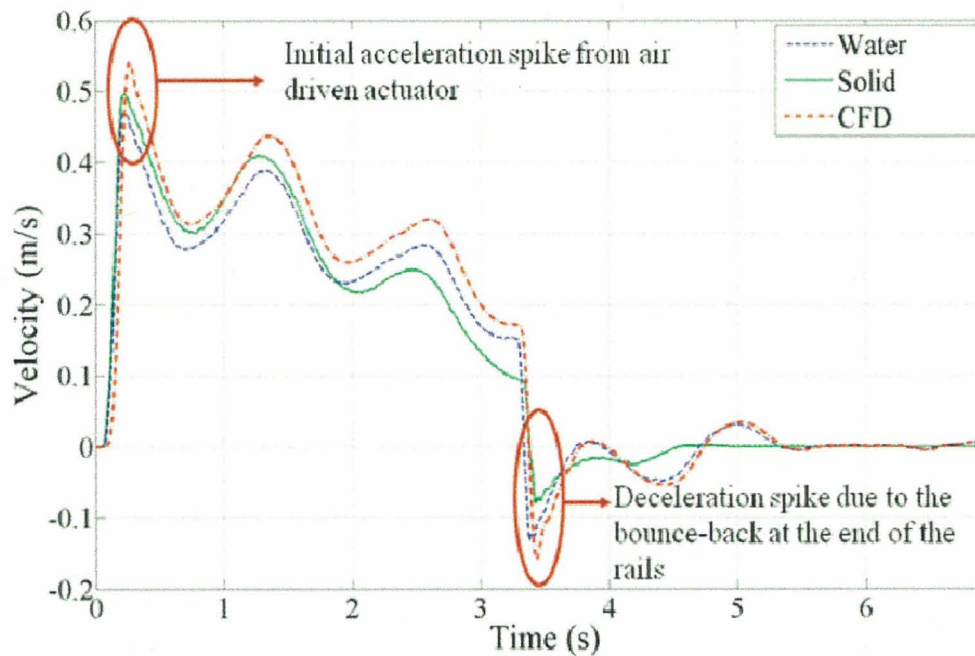




# Comparison of Results



- Non constrained base translation and container
  - Liquid and solid block tests and CFD comparison

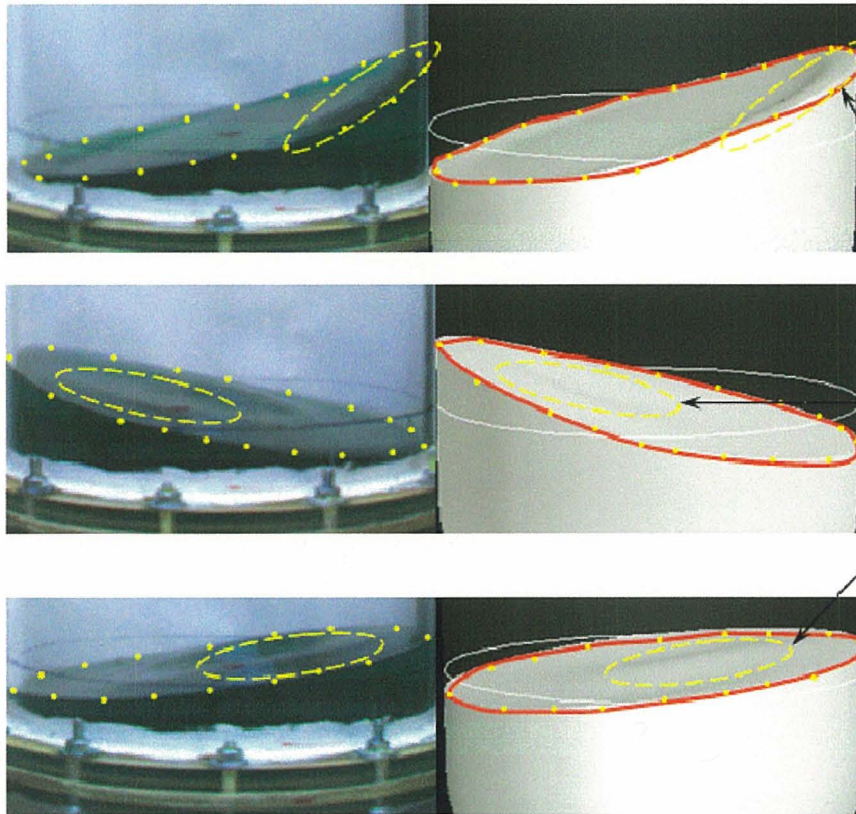




# Comparison of Results



Experimental and CFD  
surface predictions and  
Data comparisons



Examples of higher order  
details in experiment that  
appear to be captured by  
CFD model

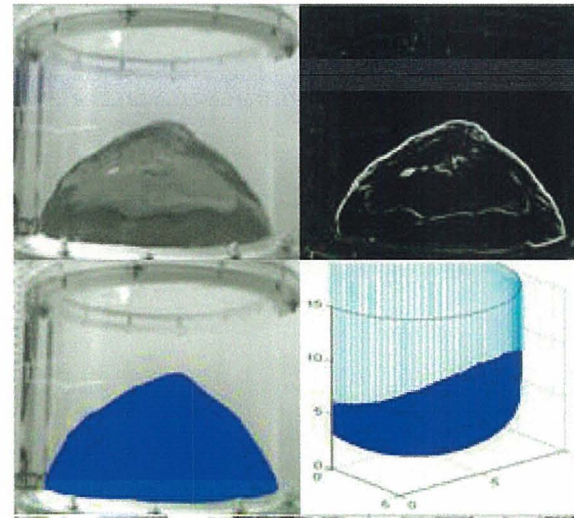




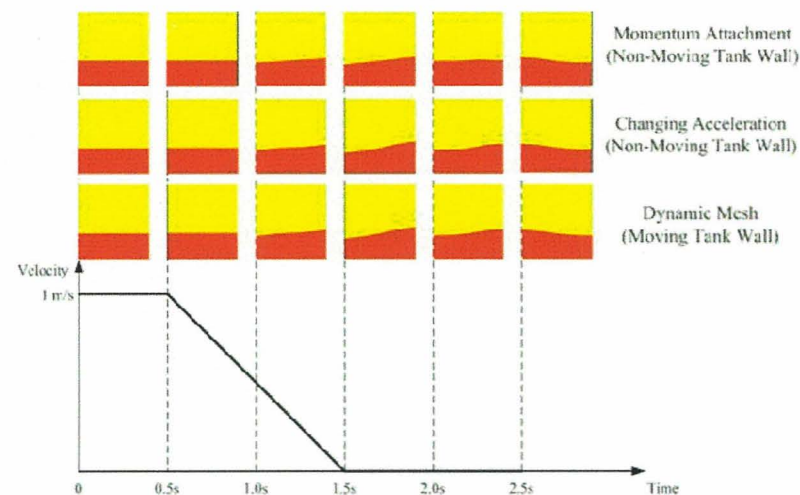
## Comparison of Results



- Binary filtering, 3-D reconstruction and surface wetting post processing techniques



- 2-D comparison of CFD methods simulating a slosh wave due to tank acceleration along one axis





## Conclusions and Future Work



- Recent advances in CFD capabilities have enabled modeling of cryogenic propellant behavior in space environments
- A wide variety of experimental and computational techniques have been developed and validated for various conditions and environments
- Ability to model complex space vehicle events in micro-gravity and advanced data acquisition techniques have been developed
- A mass gauging system designed to provide high fidelity measurements for liquid stratification and liquid/ullage positions in micro-gravity has been tested and validated

- FUTURE WORK

- Ground based testing and modeling of cryogenic LN<sub>2</sub> to capture boil-off effects
- Additional SPHERES experiments on ISS with simulated launch vehicle propellant tanks
- Flight testing of the micro-gravity mass gauging system on-board the upper stage of a launch vehicle

